Limnology of Lake Huron

A. M. Beeton & J. H. Saylor

Great Lakes Environmental Research Laboratory National Oceanic and Atmospheric Administration 2205 Commonwealth Blvd. Ann Arbor, MI 48105-1593

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l. Introduction

Lake Huron differs from the other four St. Lawrence Great Lakes since its major water input is from two other large lakes, *i.e.*, Lakes Michigan and Superior, and a large part of its basin and watershed lies in the rocky Canadian Shield. It is the second largest of the St. Lawrence Great Lakes in surface area and third largest in volume (Beeton, 1984). Previously it ranked as the fifth largest of the 283 large lakes of the world, but the ill advised water diversions away from the Aral Sea (Micklin, 1988) have resulted in the Sea becoming the seventh largest lake and Lake Huron is now the fourth largest lake in surface area.

Hydrographically Lakes Huron and Michigan (Fig. 1) sometimes have been considered one system because they are connected through the Straits of Mackinac and they are at the same altitude. Despite large exchanges of water through the Straits and a seiche which oscillates between the two lakes, Lake Huron differs from Lake Michigan, especially in water quality.

The limnology of the lake is largely determined by five geographic features, viz. the inflow of the St. Marys River, which connects Lake Huron to Lake Superior; the Straits of Mackinac; Georgian Bay and the North Channel; Saginaw Bay; and the main lake (Fig. 2). These geological features plus land use activities in the watershed appear to be the major factors determining the water quality and biota.

2. Origin and Nature of Lake Huron Basin

Lake Huron has a complicated basin containing a number of islands, shoals, and troughs associated with a glacial scour origin in rock of various degrees of scour resistance. Several advances and retreats of the North American glacier resulted in the present day basin (Hough, 1958). The last major glacial retreat apparently occurred about 6000 years ago. Radiocarbon dating indicates that present day Lake Huron appeared after the Algoma Stage about 2500 years ago.

The northeastern shore of Georgian Bay and the North Channel shore are on the edge

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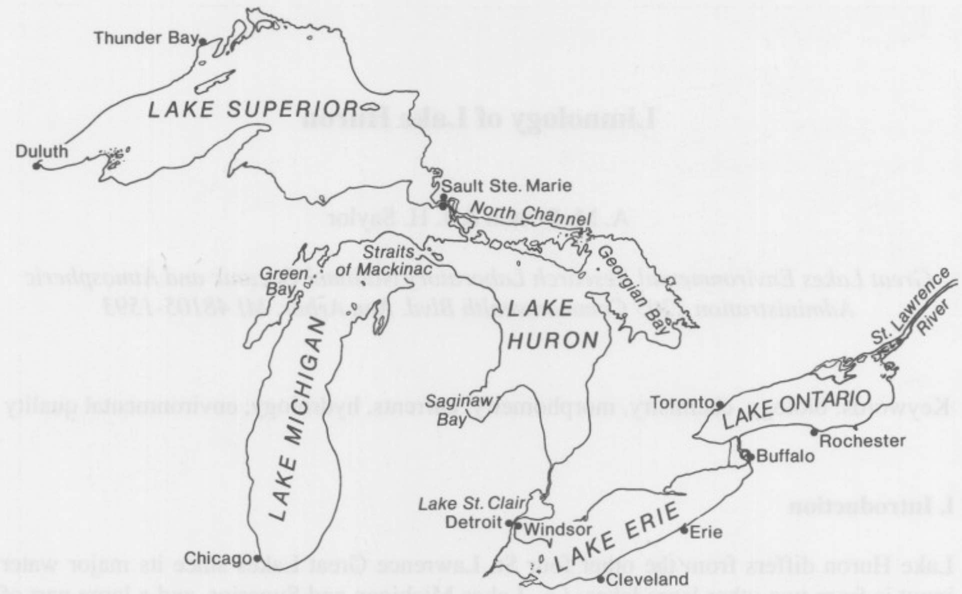


Fig. 1. St. Lawrence Great Lakes.

of the Canadian Shield (Fig. 3). The remainder of the basin is Paleozoic rock. Niagaran Dolomite is found east of the Straits of Mackinac in the several large islands and the Bruce Peninsula. Shales are along the southwestern side of Georgian Bay. Mississippian and Pennsylvanian bedrock are important in the western basin. Most of the bedrock is covered by glacial deposits of clay, sand, and rock.

3. Morphometric Data

Morphometric data for Lake Huron are presented in Table 1. Unlike small lakes, which may occupy only 10 percent of their basin, Lake Huron covers 31 percent of its basin. Also, it has a long shoreline, 325 km longer than the shoreline of Lake Superior, which is 27.5 percent larger in surface area, because of several large islands (Cockburn, Drummond, Manitoulin, St. Joseph), Bruce Peninsula, Saginaw Bay, and the tortuous shore and many small islands of Georgian Bay (Fig. 2). The maximum depth is in the central lake. Mean depths in Georgian Bay and the North Channel are 44 m and 22 m, whereas Saginaw Bay is shallow with large areas less than 10 m. The lake has a crytodepression since the deepest basin is 52 m below sea level.

4. Hydrology

Hydrologic data for monthly averages over 38 years are presented in Table 2. Over-lake precipitation has been less than 7 cm from January through July with increased precipita-

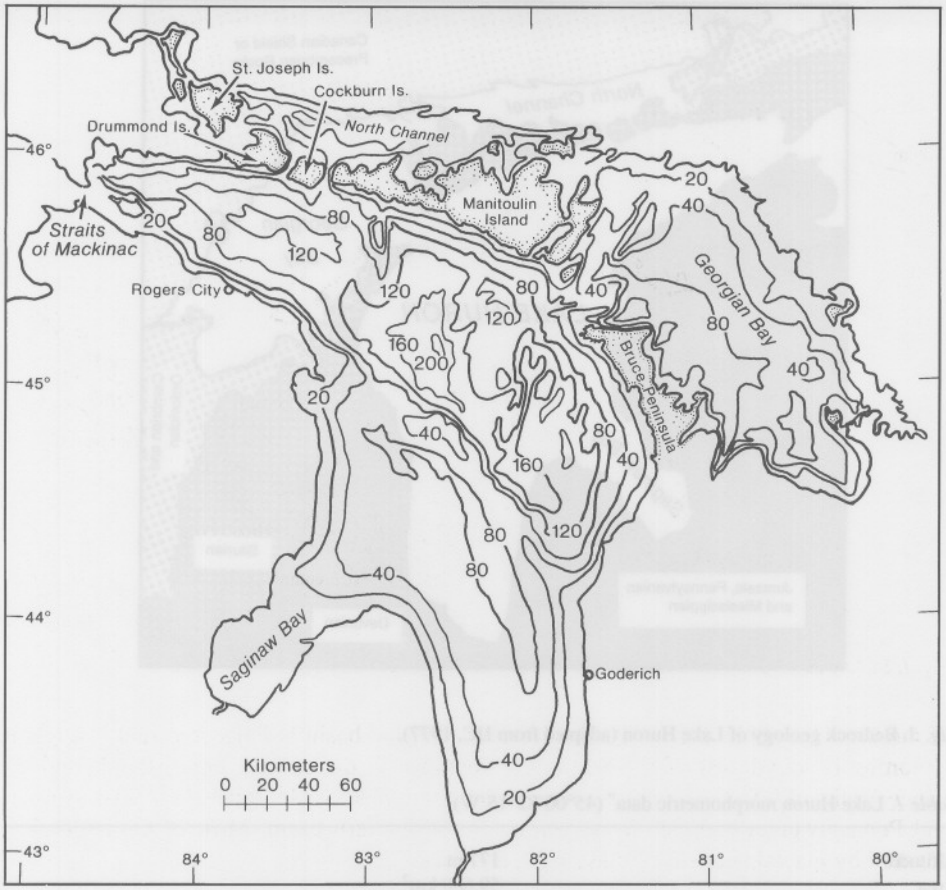


Fig. 2. Lake Huron bathymetric chart (adapted from Berst & Spangler, 1973).

tion from August through December. Average Basin runoff has been lowest in August and highest in April, in disagreement with the over-lake precipitation. The greater basin runoff in April is a consequence of snowpack melt and high soil moisture. The lake evaporation has been low in May and June and highest in November and December. The major inflows are the St. Marys River and inflow of Lake Michigan water through the Straits of Mackinac. The St. Marys River monthly average inflow has ranged from 2020 to 2543 m^3 sec^{-1}. The inflow through the Straits has been extremely difficult to determine since it is highly variable and at times a large flow from Lake Huron to Lake Michigan occurs. The net flow into Lake Huron from Lake Michigan is about 50 percent of the average flow of the St. Clair River. The monthly average outflow of the St. Clair River ranges from a low of 4828 m^3 sec^{-1} in February to a high of 5753 m^3 sec^{-1} in August. The long-term monthly average water level is 176.61±0.14 m.

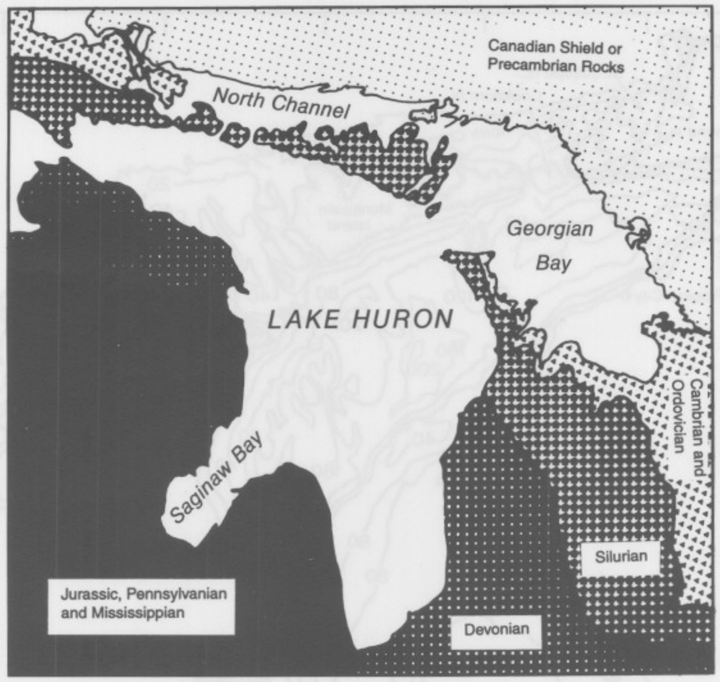


Fig. 3. Bedrock geology of Lake Huron (adapted from IJC, 1977).

Table 1. Lake Huron morphometric data* (45°00′82°15′W)

Altitude	177 m
Area	59,600 km^2
Drainage Basin	131,300 km^2
Shoreline	6,157 km
Mainland	2,973 km
Islands	3,184 km
Depth (Max)	229 m
Depth (mean)	59 m
Volume	3,540 km^2
Length	332 km
Breadth	295 km
Crypto depression depth	52 m

* Source. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. 1977 Coordinated Great Lakes Physical Data report.

5. Water Temperatures

Hydrodynamic processes in Lake Huron directly affect the chemical, biological, and ecological dynamics of the basin. Horizontal and vertical transports and mixing influence the distribution of nutrients, biota, and contaminants. The lake experiences an annual cycle of heating and cooling that takes the mean temperature of the lake both above and

Table 2. Lake Huron hydrologic data.

Hydrologic parameter	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Over-lake precipitation[1], cm	6.84	5.15	5.56	6.46	6.75	6.99	6.95	8.31	9.26	7.50	7.76	8.06
Basin Runoff[1], cm	9.64	8.88	14.36	22.79	15.96	8.28	6.13	4.90	5.83	8.07	10.14	11.08
Lake Evaporation[1], cm	9.23	4.15	3.08	1.19	0.30	0.32	1.53	4.33	7.08	8.30	10.33	11.94
Inflow from Lake Superior through the St. Marys River[2], m^3/sec	2057	2041	2020	2062	2293	2351	2409	2543	2517	2405	2401	2201
Outflow to Lake St. Clair through the St. Clair River[3], m^3/sec	4838	4828	5187	5326	5583	5675	5746	5753	5715	5662	5599	5418
Water levels[4], m, IGLD 1985	176.49	176.47	176.48	176.57	176.66	176.72	176.75	176.75	176.70	176.64	176.58	176.53

[1] 1951-1988 monthly average values expressed in units of depth over the Lake Huron surface. Hunter, T.S. & T.E. Croley, II, in preparation, Great Lakes monthly hydrologic data. Great Lakes Environmental Research Laboratory, Ann Arbor, MI.

[2] 1951-1988 monthly average flows. Data provided by the U.S. Army Corps of Engineers, Detroit District, Detroit, MI.

[3] 1951-1988 Monthly average flows. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1988. Lakes Michigan-Huron outflows. Chicago, IL and Cornwall, Ontario.

[4] 1951-1988 monthly average levels as recorded by the National Ocean Service at Harbor Beach, Gage No. 5014.

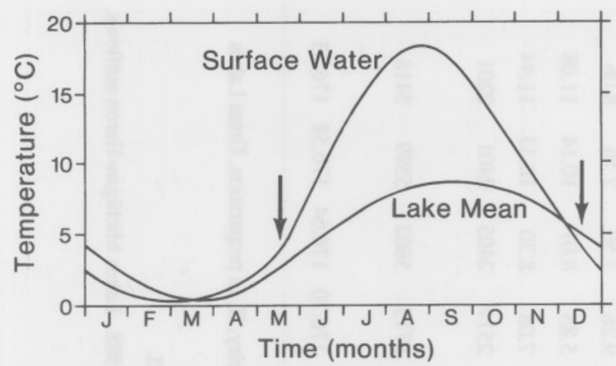


Fig. 4. Annual temperature cycle of Lake Huron (from IJC, 1977).

below the temperature of maximum density for freshwater, which is close to 4°C. Because the water density distribution is determined almost solely by the temperature distribution, it is of fundamental importance to understand the thermal characteristics.

"Overturn" is a descriptive term that denotes vertical mixing from the top to bottom of an entire lake. In shallow lakes, a complete overturn may occur. Lakes that are extremely deep or sheltered from wind may experience only a partial or incomplete overturn. Complete overturn occurs when the lake is isothermal and, therefore, of uniform density. The thermal resistance to vertical water mixing is then at a minimum, and relatively light winds can cause complete circulation (Welch, 1952). Lake Huron's mean temperature passes through that of maximum density twice a year, as it does in many lakes in the temperate zone (Fig. 4). In Lake Huron, a fall overturn occurs when the lake begins to cool. It is characterized by the sinking and convective mixing of cooler, dense water from the surface, displacing warmer and lighter water below. Cooling continues until the lake reaches the temperature of maximum density. The water mass then offers little resistance to mixing by wind energy imparted by late fall and winter storms, and mixing can continue until the following spring if the lake is not ice covered. Measurements of temperature distributions during winter reveal that the lake remains nearly isothermal vertically as the water cools even at great depths to temperatures as low as 1 to 2°C (Miller & Saylor, 1981). It is noted that while water at the lake surface is of maximum density at a temperature close to 4°C, the temperature of maximum density decreases slightly with increasing depth (about 0.06°C per each 31 m increase in depth) (Eklund, 1963). A spring overturn occurs in Lake Huron if the lake has been ice covered and when the surface water is heated to the temperature of maximum density. It then sinks and displaces the colder, less dense water below, again causing complete mixing under conditions of sufficient wind energy.

The water in shallow depths around the perimeter of the lake warms sooner in spring than that in deeper water where the overturn can still be in progress. Horizontal temperature gradients then appear in coastal water setting up a "thermal bar" feature as described by Rodgers (1965). An illustration of the phenomenon is shown in the temperature distributions shown in Fig. 5. The densest surface water is at the 4°C isotherm. Surface water converges and sinks near this isotherm and diverges and upwells in the less dense water that is located both onshore and offshore. A two-celled vertical circulation evolves that

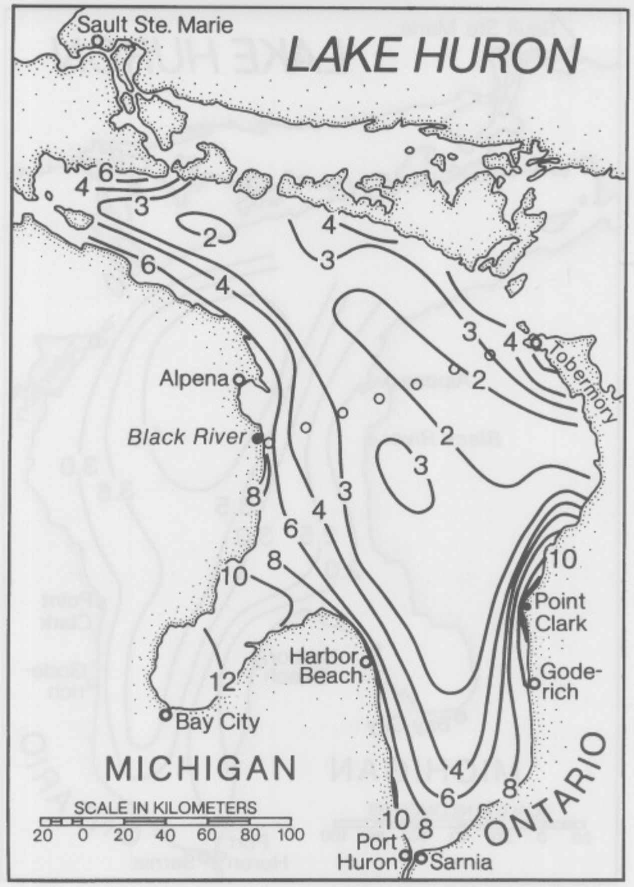


Fig. 5. Surface water temperatures (°C) of Lake Huron, May 17–25, 1971 (from IJC, 1977).

completes the classical "thermal bar" development (Huang, 1970). A fall "thermal bar" can also occur as water is cooled most rapidly in the shallow water about the basin's perimeter. Fig. 6 shows observations in the late stages of such a front in 1974 (Miller & Saylor, 1981).

Stratification occurs when Lake Huron's water is divided into nearly horizontal layers having distinct temperature differences. Sharply defined boundaries in water density often exhibit differences in chemical and biological characteristics as well. When the net radiation to the lake is positive, typically from March through September, a balance is maintained in the water column between vertical mixing caused by the surface wind stress and the buoyancy of the less dense surface water. Wind driven mixing tends to distribute the temperature uniformly through the water column while buoyancy tends to establish vertical gradients with the warmer water at the surface and cooler water at greater depth. The result is the development of a surface mixed-layer separated from a deeper layer of cold water by a thermal transition zone (thermocline). In summer and early fall these density differences between layers are large enough that the lake's

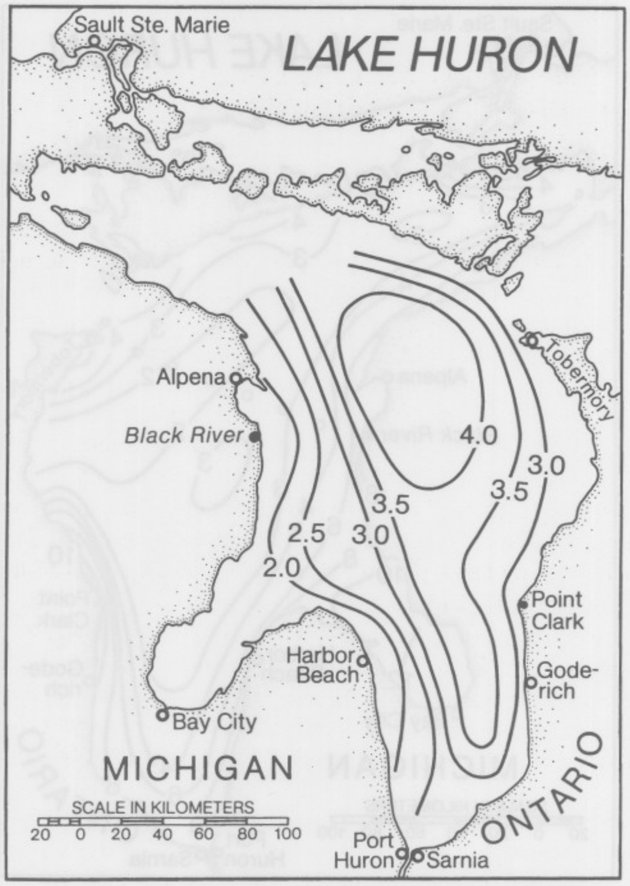


Fig. 6. Mean monthly water temperatures (°C) in January, 1975 (from Miller & Saylor, 1981).

thermal structure may approximate a two-layer system, like oil floating on water. In winter, weak stratification may occur during short intervals when cold, less dense water is layered over warmer, denser water (Miller & Saylor, 1981).

The upper layer is easily transported by wind energy, and mass in the lower layer adjusts in response. In the shallower embayments and connecting waters the temperature variations are greater, as in shallow lakes, with warmer surface water during summer and more extensive ice cover in winter (Bennett, 1988). Wind mixing can prevent a permanent, seasonal thermocline from forming in the shallowest bays, as in the shallow reaches of Saginaw Bay (Danek & Saylor, 1977).

6. Storm Surges and Seiches

When steady wind blows across the lake surface, the equilibrium level of the water surface is depressed along the upwind coast and elevated along the downwind coast. For wind blowing along a channel of finite length and uniform depth, the depression and elevation at its ends are of the same amplitude and proportional to the square of the wind speed, the length of the channel, and the inverse of its depth. Because of Lake Huron's great depth, storm surges are usually of small magnitude except in the shallow bays, most notably Saginaw Bay and Georgian Bay (Allender & Green, 1976a; Murty, 1982). In both embayments, severe flooding and shore erosion occur when wind piles up water in their shallow reaches.

Winds are usually not steady for long intervals of time and realistic hydrodynamic modelling of storm surges now requires sophisticated numerical techniques (Schwab, 1992). Following a storm surge generation event, the return of the lake surface to a level position always stimulates seiche propagation. Lake Huron has a unique set of seiche modes that depend upon the lake's configuration, dimensions, and bathymetry. Several of its embayments and harbors are also characterized by unique seiche oscillations. Seiches are the normal modes of oscillation of the lake surface that occur after an initial disturbance from its level equilibrium position, analogous in some respects to the waves that slosh back and forth at distinct periods in a bathtub or in a coffee cup. Several of the longest period surface seiches of Lake Huron have been estimated numerically (Rockwell, 1966; Schwab & Rao, 1977), and verified observationally (Saylor & Sloss, 1976). The longest surface seiche has a period close to 6.7 hours. Several of the shorter period lake modes of oscillation and those of the principal embayments have also been confirmed by observation (Allender & Green, 1976a). The connection of Lakes Huron and Michigan through the Straits of Mackinac permits a combined seiche of the two basins, with a nodal point (a point of zero surface displacement) required in the Straits region. The period of the seiche is a little longer than two days and it drives currents eastward and westward through the Straits constriction at speeds that can be quite strong (Saylor & Sloss, 1976). This seiche, many seiche modes of each of Lake Huron and Lake Michigan, semidiurnal tides, and other forces drive currents which can be measured in the Straits area; this region is a very rich and rewarding site for dynamical studies.

Seiches also occur on the interfaces that separate layers of different density in a stratified lake. Wind which forces the water surface to tilt (storm surge) also displaces the layer interface (Fig. 7). The surface level increases at the downwind end of the lake and the thermocline is depressed. As occurs with long waves propagating at the lake surface following its distortion (surface seiches), internal seiches and other wave forms result from the decay of an initial thermocline set-up. Wave speeds for seiche-like motions are much less than their surface counterparts, and wave periods for very long-length internal waves in Lake Huron would range from many days to weeks if they did indeed propagate as internal seiches. But effects of the earth's rotation cause these waves to take a different wave form in large lake basins (Mortimer, 1963). Most of this energy is then focused in internal waves which have the near-inertial period of about 17 hours, and persistent currents that complete one clockwise, nearly circular orbit in that time are ubiquitous and energetic during the stratified season (Sloss & Saylor, 1976).

7. Water Movements

Lake Huron currents are driven by three major forces. The hydraulic flow-through of water that enters the lake from Lakes Superior and Michigan and from tributary streams and exits at Port Huron in the St. Clair River is an important force near the river mouths

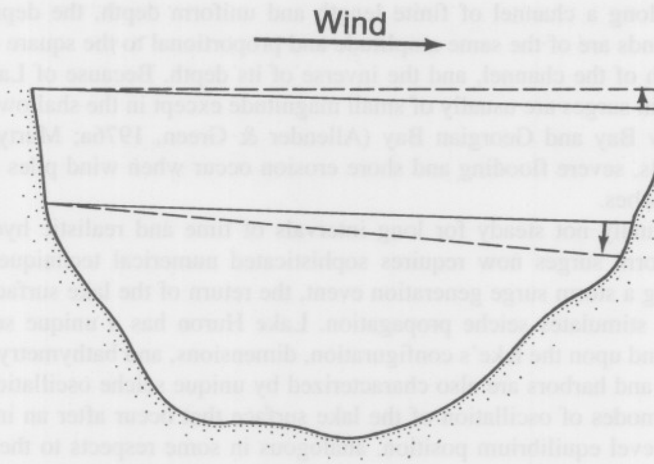


Fig. 7. Wind blowing across the lake elevates the water surface and depresses the thermocline from the undisturbed level along the downwind shore.

and sources. Wind acting on the water surface generates wind waves and storm surges and also propels water currents. The wind driven flows can penetrate to great depths in winter storms and governs, to a large extent, the depth of the surface mixed-layer during the seasons of stratification. Lastly, horizontal pressure differences caused by wave motions and by thermal forcing and long-lasting spatial variations in thermocline depths cause currents. Wave motions, both surface and internal, perturb the level planes of the equilibrium pressure field and drive currents. These important long-period motions (wave periods longer than 1 or 2 hours) cause currents that are barotropic for surface waves (*i.e.*, uniform throughout the water column from top to bottom causing net transport past a location) and baroclinic for internal waves (*i.e.*, in exactly opposite directions in the top and bottom layers causing an integrated surface to bottom transport that is negligible).

Gravitational forces are always acting to minimize the potential energy. The energy is at a minimum when the water surface and internal density interfaces are level with the equipotential planes. Therefore, accumulations of dense or light water along these planes always produce pressure gradients that induce water movements from high to low pressure. If these gradients are balanced by the inertial forces caused by the earth's rotation, the flow is-said to be in geostrophic equilibrium. The geostrophic currents play a very important role in shaping the circulation patterns in both large lakes and, especially, the oceans.

In the northern hemisphere the forces are such that looking in the direction toward which the current is flowing, the lighter water is piled to the right hand side. There are many important inferences concerning the seasonal circulation of Lake Huron that can be made from the long-lived temperature distributions we noted earlier. Spring heating, fall cooling, "thermal bars," and other seasonal lake-wide temperature variations play roles in shaping the circulation patterns. Harrington (1895) deduced from drift bottle studies a prevailing counterclockwise flow pattern in Lake Huron in summer as he did in the other deep Great Lakes. Church (1942; 1945) studied the annual temperature cycle of Lake

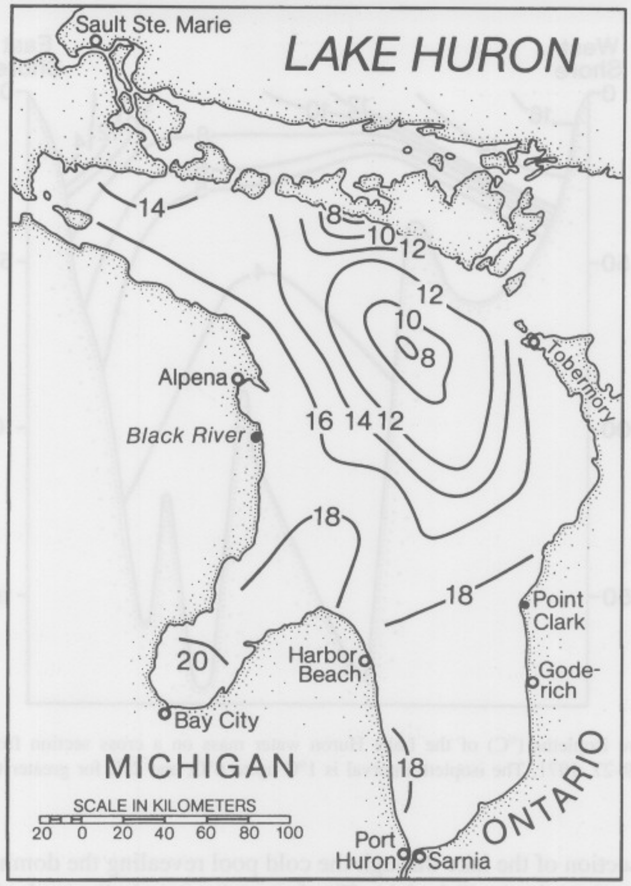


Fig. 8. Surface water temperatures (°C) of Lake Huron, July 19–27, 1971 (from IJC, 1977).

Michigan using repeated bathythermograph casts from a railroad car ferry that traversed the midsection of the lake on a frequent and regular schedule. He inferred circulation patterns from the structure of observed water density distributions and geostrophic principles. Application of a dynamic height method to compute geostrophic currents in Lake Huron from lake temperature distributions was made by Ayers *et al.* (1956). They used temperature information collected on multivessel, one-day-long synoptic cruises of the lake to determine circulation. However, the application of this technique to synoptic conditions proved in time not to be very useful because of the large thermocline displacements caused by internal waves that were revealed in subsequent measurement programs. The synoptic, one-day surveys were seriously contaminated by internal wave "noise."

The temperature variations that start in spring with the "thermal bar" and which are manifested later in the season as large pools of cold, dense water centered over the deep bathymetric basins are regular, annual features of the lakes thermal regime. Fig. 8 shows surface water temperatures in 1971 which are typical of the late July time period. Fig. 9

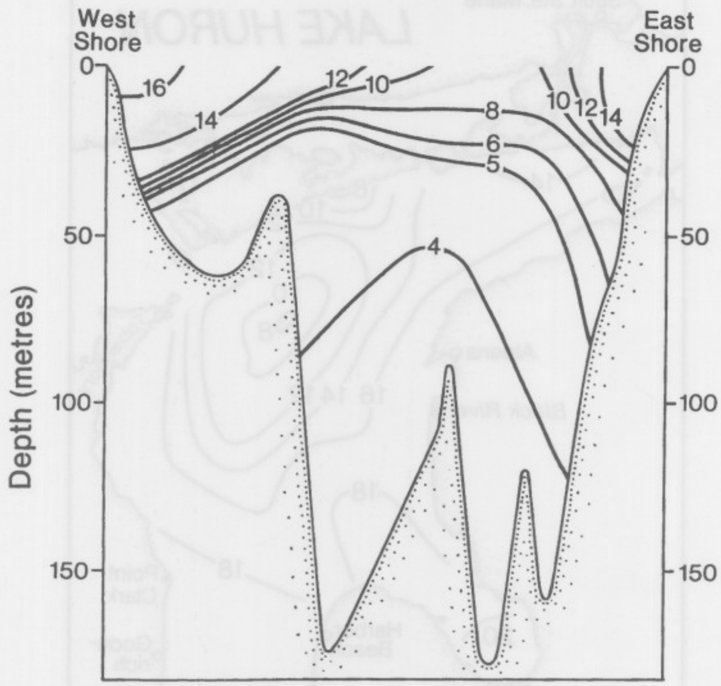


Fig. 9. Temperature isopleths (°C) of the Lake Huron water mass on a cross section from Black River to Tobermory, July 19–27, 1971. The isopleth interval is 1°C up to 6°C, and 2°C for greater temperatures (from IJC, 1977).

shows a cross section of the lake through the cold pool revealing the doming of isotherms over the deep northern basin of the lake. The feature is very similar to the isotherm distributions observed in Lake Michigan by Church (1942; 1945). Lighter water surrounding cold, dense water is indicative of counterclockwise flow about the basin, with convergence and sinking of surface water along the outer margins and the divergence of surface water and upwelling over the cold core. This pattern prevails long into the summer months, and the anticipated currents associated with it persists also. Sloss & Saylor (1976) examined extensive current meter records obtained by the Federal Water Pollution Control Administration (an agency which later became part of the Environmental Protection Agency at its founding) to determine a mean summer circulation pattern as shown in Fig. 10. The lake currents flow in a cyclonic pattern. Though this pattern is routinely disrupted by energetic wind storms, mean currents averaged over long time intervals maintained this basic structure.

Because the cyclonic circulation during summer is similar to that observed in the other deep Great Lakes (Saylor *et al.*, 1981), we note that there has been considerable discussion as to whether the density distributions drive the currents or vice versa (cf. Bennett, 1975; Emery & Csanady, 1973; Wunsch, 1973). Most recently the cyclonic mean circulation of Lake Ontario has been explained in terms of topographic wave propagation which follows excitation by strong wind impulses. Topographic waves have been observed in both Lakes Ontario and Michigan but have not been investigated in Lake Huron. Because

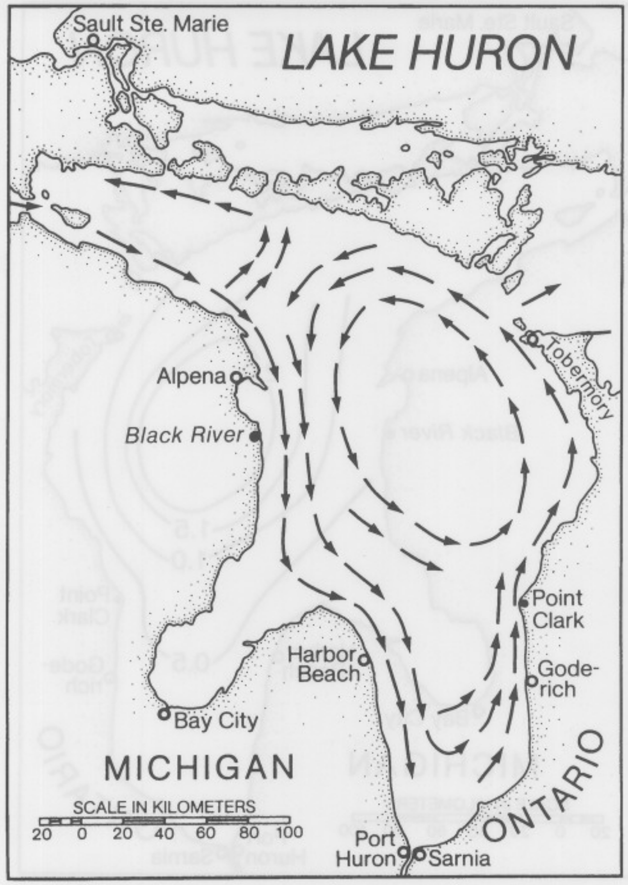


Fig. 10. Summer averaged circulation pattern in the epilimnion of Lake Huron (from Sloss & Saylor, 1976).

of basin similarities, they are very likely to occur in this third lake as well.

Winter current studies reveal continued cyclonic flow more intense than that observed during summer (Saylor & Miller, 1979). The lake-wide density variations that occur fit the pattern of lightest water about the perimeter of the lake and densest water over the deep basins (Fig. 11). In winter though, the density gradients are not strong enough to drive the observed currents, lending support to arguments that the temperature field is determined, to a large extent, by its adjustment to the current patterns. The topographic wave theory for driving mean flow fields fits these observations. Currents in Georgian Bay are less well understood, but during summer they also reveal a counterclockwise bias (IJC, 1977; Bennett, 1988). Saginaw Bay has its own circulations which are closely tuned to wind forcing and seiche interactions (Allender & Green, 1976a, 1976b). Water in this shallow embayment responds quickly to changing wind fields and is especially sensitive to winds directed along the bay's axis (Danek & Saylor, 1977).

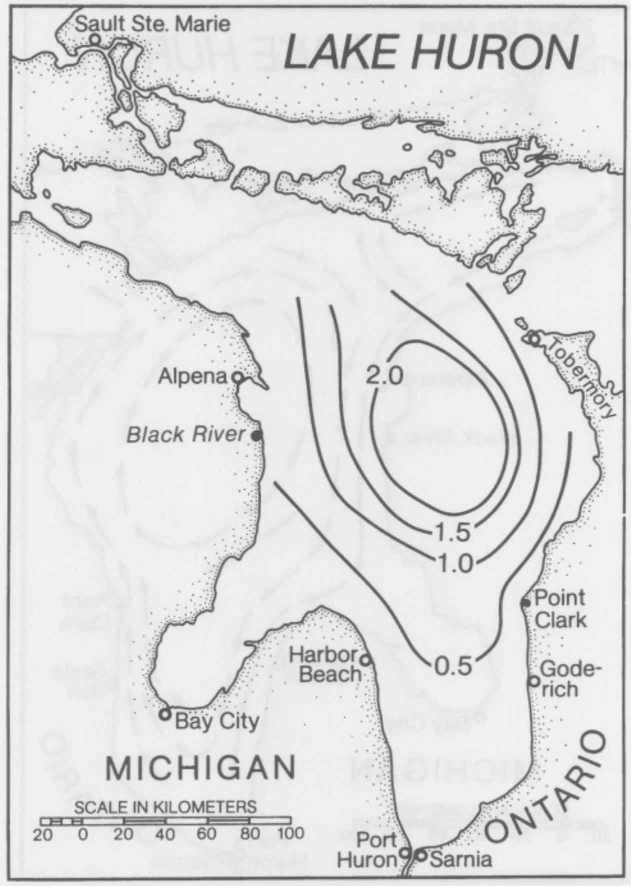


Fig. 11. Mean monthly water temperatures (°C) of Lake Huron in March, 1975 (from Miller & Saylor, 1981).

Superimposed on the lake-scale mean flows are currents generated by strong wind impulses. When wind blows across a lake, surface water is transported downwind by the stress. The level at the downwind end of the lake rises, and the resulting pressure gradient causes a return flow in the deeper parts of the basin. The force balance is between the wind stress and the surface slope, and a mass balance is achieved between the surface current and the return flow. In lakes with sloping bottoms this causes currents to flow with the wind in the shallower water along the coasts and weaker return currents upwind in the deeper parts. The resulting current flow is a two-gyre pattern with a clockwise flowing cell in the half of the lake to the left of the wind vector and a counterclockwise flowing cell in the half to the right. This pattern is the dominant response to steady wind forcing and has been described by numerous investigators (*e.g.*, Birchfield, 1967, 1969, Csanady, 1967,1968; Murty & Rao, 1970). After the stress decays, the two-gyre pattern can sometimes propagate about the basin as simple first mode topographic waves (Saylor *et al.*, 1981) or take more complex forms. The circulation response to wind forcing has

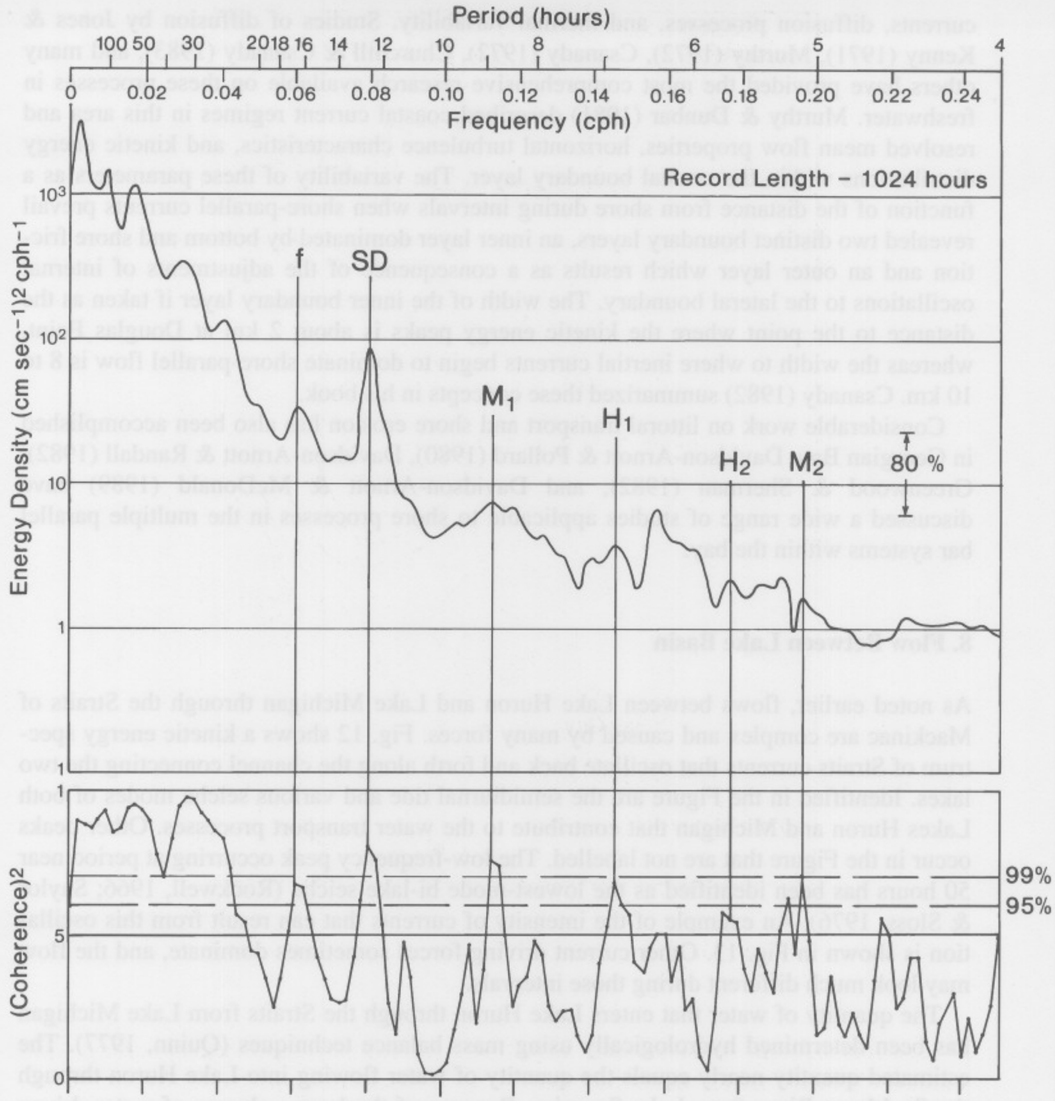


Fig. 12. Cross–spectrum of two current meter recordings from the Straits of Mackinac which reveals inertial (f), semi–diurnal tidal (SD), Lake Michigan seiche (M_1 and M_2), and Lake Huron seiche (H_1 and H_2) components of the flow between lake basins.

been intensively researched for application to the Great Lakes, and excellent reviews have been published by Csanady (1984), Boyce *et al.* (1989), and Schwab (1992). A book on circulation modelling was published by Simons (1980), and a book on coastal hydrodynamics was written by Csanady (1982).

Many physical limnology studies of fundamental importance have been performed in the Douglas Point area of southern Lake Huron. The siting of a nuclear power generating station at this location provided the impetus for wide-ranging investigations of coastal currents, diffusion processes, and thermal variability. Studies of diffusion by Jones & Kenny (1971), Murthy (1972), Csanady (1972), Churchill & Csanady (1983), and many others have provided the most comprehensive research available on these processes in freshwater. Murthy & Dunbar (1981) described coastal current regimes in this area and resolved mean flow properties, horizontal turbulence characteristics, and kinetic energy distributions within the coastal boundary layer. The variability of these parameters as a function of the distance from shore during intervals when shore-parallel currents prevail revealed two distinct boundary layers, an inner layer dominated by bottom and shore friction and an outer layer which results as a consequence of the adjustments of internal oscillations to the lateral boundary. The width of the inner boundary layer if taken as the distance to the point where the kinetic energy peaks is about 2 km at Douglas Point, whereas the width to where inertial currents begin to dominate shore-parallel flow is 8 to 10 km. Csanady (1982) summarized these concepts in his book.

Considerable work on littoral transport and shore erosion has also been accomplished in Georgian Bay. Davidson-Arnott & Pollard (1980), Davidson-Arnott & Randall (1982), Greenwood & Sherman (1982); and Davidson-Arnott & McDonald (1989) have discussed a wide range of studies applicable to shore processes in the multiple parallel bar systems within the bay.

8. Flow Between Lake Basin

As noted earlier, flows between Lake Huron and Lake Michigan through the Straits of Mackinac are complex and caused by many forces. Fig. 12 shows a kinetic energy spectrum of Straits currents that oscillate back and forth along the channel connecting the two lakes. Identified in the Figure are the semidiurnal tide and various seiche modes of both Lakes Huron and Michigan that contribute to the water transport processes. Other peaks occur in the Figure that are not labelled. The low-frequency peak occurring at period near 50 hours has been identified as the lowest-mode bi-lake seiche (Rockwell, 1966; Saylor & Sloss, 1976). An example of the intensity of currents that can result from this oscillation is shown in Fig. 13. Other current driving forces sometimes dominate, and the flow may look much different during those intervals.

The quantity of water that enters Lake Huron through the Straits from Lake Michigan has been determined hydrologically using mass balance techniques (Quinn, 1977). The estimated quantity nearly equals the quantity of water flowing into Lake Huron through the St. Marys River from Lake Superior. Because of the large volumes of water driven back and forth through the channel by seiches and other forces, the mean flow is difficult to measure directly. The mean discharge through the narrowest constriction would produce a current speed of about 2 cm s^{-1}, a very small speed when compared with those caused by the other forces. Saylor & Sloss (1976) measured currents through this cross section during 1973 that revealed a very important seasonal dependence however.

Prevailing westerly and southwesterly winds during summer cause the thermocline depth to be greater at the Lake Michigan end of the Straits than it is at the Lake Huron end (National Climatic Center, 1975). The difference in thermocline depth sets up a pressure gradient that forces cold, hypolimnion water to flow into Lake Michigan during the stratified season, opposite to the mean flow into Lake Huron. Averaged over the length of its summer occurrence (about 100 days during 2 years of observation), a large quantity of

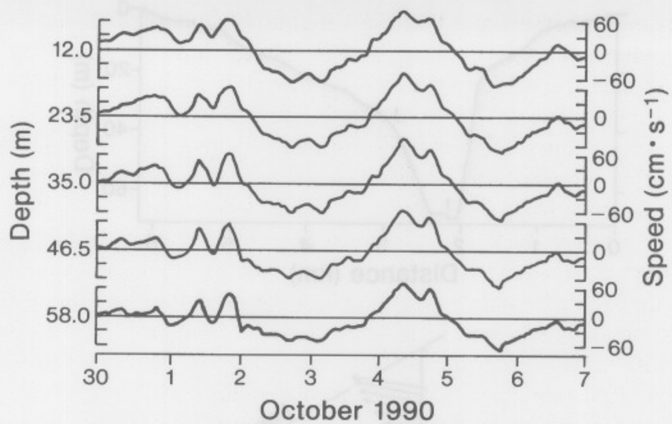


Fig. 13. The east directed component of current velocity through the Straits of Mackinac from September 30 to October 6, 1990. Positive speeds (above the horizontal axis) are east–directed currents, negative speeds are west–directed. Five measurement levels are shown, with the depth below the water surface shown for at the left of the recordings.

Lake Huron water is advected into Lake Michigan's northern basin. The quantity of this inflow is sufficient to decrease the residence time of Lake Michigan from 137 to 69 years (Quinn, 1977). Profiles of current velocity averaged over the stratified season of 1990 are shown in Fig. 14. These profiles were obtained by the Great Lakes Environmental Research Laboratory using Acoustic Doppler Current Profilers placed at the bottom of the deep channel that connects the two lakes. The profilers measure the horizontal current velocity by transmitting acoustic pulses from four transducers upward through the water column. The transmitted signal is reflected from minute particles in the water, such as algae and clay or silt size particles, back to the acoustic transducer. The Doppler shift of the reflected waves is analyzed within the instrument and transformed into water velocity components. The measurements were taken at l-m intervals from close to the transducer heads to close to the water surface. As a point of interest, the profiles recorded during 1990 when averaged over the length of the stratified season yield almost exactly the mean profile of current velocity reported by Saylor & Sloss (1976). The volume of inflowing Lake Huron water is about twice the amount of the average Lake Michigan discharge, necessitating the outflow (above the thermocline) of three times the average discharge of water from Lake Michigan during this time interval.

Accelerated flushing of Georgian Bay water by Lake Huron dilution has also been reported (IJC, 1977; Bennett, 1988). Again the wind-driven distribution of thermocline depth is the major causative factor. If the Main Channel connecting Lake Huron with Georgian Bay did not exist, upwelling would persist along the west side of the bay in response to the prevailing winds. Because of the Main Channel connection to the lake, the upwelling in Georgian Bay and downwelling along the east coast of Lake Huron sets up a pressure gradient as in the Straits region, with hypolimnetic water forced into Lake Huron by differences in thermocline depth. The enhanced inflow of Lake Huron surface water into the bay is important to the bay's heat and nutrient budgets and thereby influences biological productivity.

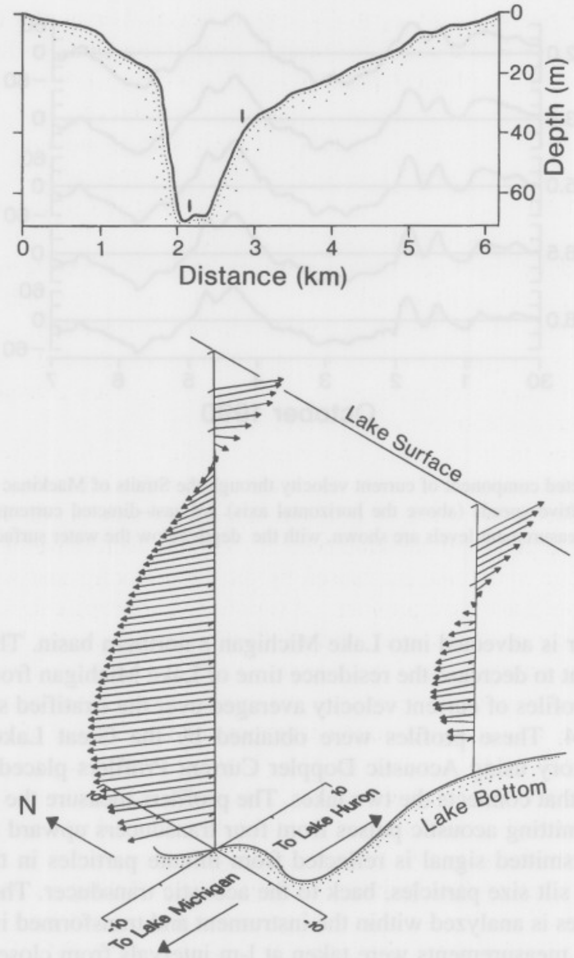


Fig. 14. Current recordings from two Straits of Mackinac acoustic profilers which have been averaged over a 100–day–long period of density stratification in the summer of 1990. The scale for current speed along each horizontal axis is 12 cms^{-1}. Currents above the thermocline flow into Lake Huron, those below flow into Lake Michigan. The average thermocline depth is shallower on the north side of the Straits than it is on the south because of dynamics governed by the earth's rotation.

9. Optical Properties

Transparency relates to the water's ability to transmit light such as direct solar radiation, indirect radiation (light from the sky), or light from an artificial source. Transparency is a primary factor controlling the depth of photosynthesis and other biological and chemical processes. The radiation that penetrates the water surface is either absorbed or reflected in the water. The relative decrease in intensity with depth of any light wavelength is described by means of vertical extinction coefficients. Other optical measurements such as those with transmissometers or Secchi discs can in theory be related with the vertical extinction coefficients.

Transparency varies vertically, spatially, and on seasonal or shorter time scales. Much of the vertical variance is related to the seasonal water temperature variations and the role it plays in determining biological productivity. Lateral variations are caused by wind stress and circulation, the presence of boundaries, and uneven spatial distributions of chemical and biological properties. Factors that determine the amount of light that penetrates the water column include the light intensity at the lake surface, its angle of incidence, and the amount and characteristics of the dissolved and suspended materials. The light is absorbed or reflected and scattered by these materials, with the latter usually controlling the depth of light penetration. Absorption by dissolved materials is important in determining water color (Hutchinson, 1957). Pure water is most transparent for wavelengths of 430 to 580 nm, the blue and green portions of visible light incident at the lake surface. The pure water spectral window is also observed in the Lake Huron water mass, though the spectral window of maximum transparency does vary seasonally and from one Great Lake to another as shown by Beeton (1962).

Spatial variations in transparency are related mainly to distributions of suspended materials. These in turn are related to particle composition and size, water depth, proximity to shore and tributary inputs, storm activity and erosion, depth of the upper mixed-layer, atmospheric inputs, and plankton concentrations to name several. Perhaps the most important short-term variations are caused by plankton blooms and wind and rainstorm activities. The latter cause most pronounced variations in transparency close to the coasts. Transparency in Saginaw Bay and southern Lake Huron was studied by Beeton (1958). A chart he prepared showing average Secchi disc transparency is shown in Fig. 15. Variations in transparency correlated with the inflow of Lake Huron water into the outer reaches of Saginaw Bay along its northwest shore and the outflow of bay water eastward across the tip of the Michigan thumb. The plume of turbid Saginaw Bay water often extends southward along the western shore of the lake to Port Huron (IJC, 1977). These patterns are similar to those reported by Ayers *et al.* (1956). Also noted were transparencies that were normally greatest offshore over the deepest basins, conforming with the water surface temperature distributions and deep basin upwellings supported by the mean circulation patterns (Fig. 16). Localized shore erosion sediment inputs along the southeast Ontario coastline also cause plumes of highly turbid water (IJC, 1977). Inflows from tributary streams and from the St. Marys River inject more turbidity along the coasts and heighten the nearshore contrasts. Our studies show that turbidity is being reduced (water transparency increased) in Saginaw Bay apparently due to water filtration processes by the recently established zebra mussel communities in the lake shallows.

Suspended materials, both organic and inorganic, have considerable effect on light penetration. Light penetration is reduced as water turbidity increases. Natural light penetration can be limited to a very thin zone at the water surface during extremely turbid conditions. Clay and silt size particles, organic material, and plankton produce most of the turbidity in the coastal reaches of Lake Huron. Larger particles settle rapidly and are little affected by variations in water temperature or stratification. Thus, a natural separation occurs based on particle size and composition. Organic material tends to concentrate just above or within the thermocline as settling is impeded by the underlying water of greater density and viscosity (Welch, 1952). Another turbid layer exists as a "nepheloid layer" suspended just above the lake bottom in deeper water during stratified conditions (Eadie *et al.*, 1984). There have been few direct measurements of suspended inorganic solids in Lake Huron. Turbidity has been used as an indicator of these concentrations, but

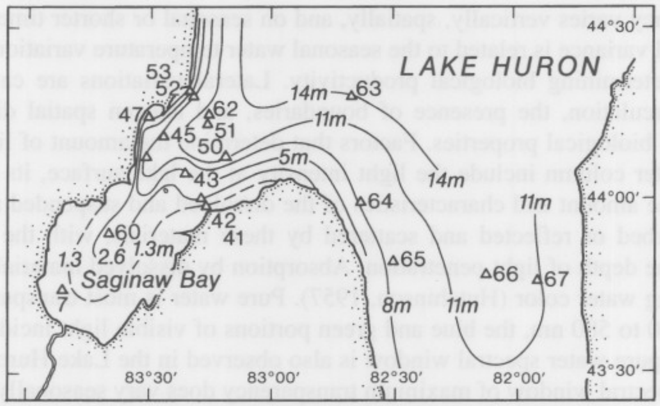
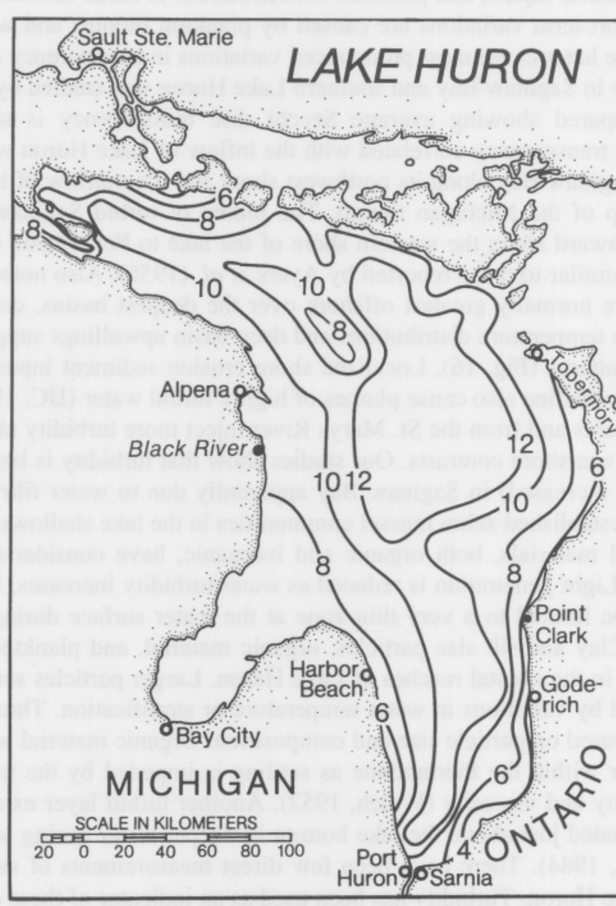


Fig. 15. Average Secchi disc transparency (m) in Saginaw Bay and adjacent Lake Huron, June to August 1956 (from Beeton, 1958).



such measurements determine the concentration of all of the suspended materials, not just the inorganic fraction. We can presume though, that the suspended sediment distributions bear very close resemblance to the water transparency distributions.

10. Chemical Characteristics of Lake Huron

The chemistry of Lake Huron is closely related to its physical features and the inflow of waters from Lake Michigan, St. Marys River, and Saginaw Bay. The physical features are the islands and peninsulas which separate Georgian Bay and the North Channel from Lake Huron proper. A number of tributaries and point source inputs, *e.g.* from municipal sewage treatment plants, have local input in the North Channel and Georgian Bay as does Goderich, Ontario in the southern basin and Rogers City, Michigan in the northern basin of Lake Huron proper.

Based on the chemical characteristics of the waters sampled in 1974 (IJC, 1977) and in 1980 (Moll, *et al.* 1985) eight water masses usually can be identified (Fig. 17). They are Central Lake Huron, Southern Lake Huron, Georgian Bay proper, Straits of Mackinac, North Channel/St. Marys River inflow, North Channel proper, nearshore zone of Georgian Bay and the mouth of Saginaw Bay/nearshore zone of Southern Lake Huron. Moll *et al.* (1985) found six to nine water masses based on cluster analysis/principal components analysis. The eight water masses we have identified are generally compatible with those identified by Moll *et al.* (1985). The authors of the IJC (1977) report divided Lake Huron into 19 segments. An EPA scheme divided the lake into 10 segments. Both of these schemes place more emphasis on local inputs than Moll *et al.* (1985).

The inflow of the St. Marys River has usually been referred to as Lake Superior water. This is probably correct in regards to conservative ions, *e.g.* chloride and specific conductance, since the inflowing St. Marys water is closely similar to that of Lake Superior for these properties. This is not true for nutrients, *i.e.*, nitrogen and phosphorus, since upstream industrial and municipal discharge enter the river. This increased nutrient load is evident in the higher nutrient content water flowing from the St. Marys River into the North Channel.

The information and conclusions in this section are largely based on the two extensive lake-wide surveys of 1974 (IJC, 1977) and 1980 (Moll *et al.*, 1985). Details on the chemical limnology of Georgian Bay and the North Channel are summarized by Weiler (1988). A good source of information on nearshore waters of western Lake Huron is in Basch *et al.* (1980).

Data from the 1974 (IJC, 1977) and 1980 (Moll *et al.*, 1985) lake-wide surveys show that throughout most of the year and across the lake, total phosphorus (Fig. 17), soluble reactive phosphorus, and ammonium concentrations were uniformly low with minor seasonal variations. Nitrate and silica concentrations did have small seasonal changes and areal patterns (Fig. 17) likely determined by uptake by phytoplankton and inflow of waters with high or low concentrations of these nutrients. The greatest concentrations of nitrate and silica in the epilimnion occurred in spring when the water column was homothermous (Moll *et al.*, 1985). Nitrate values were around 0.28 mg N l^{-1} and silica values were about 1.5 mg l^{-1}. Nitrate was 0.24 mg N l^{-1} and silica 1.0 to 1.2 mg l^{-1} in the

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Fig. 16. Secchi disc transparency (m) in Lake Huron in August, 1954 (from Ayers et al., 1956).

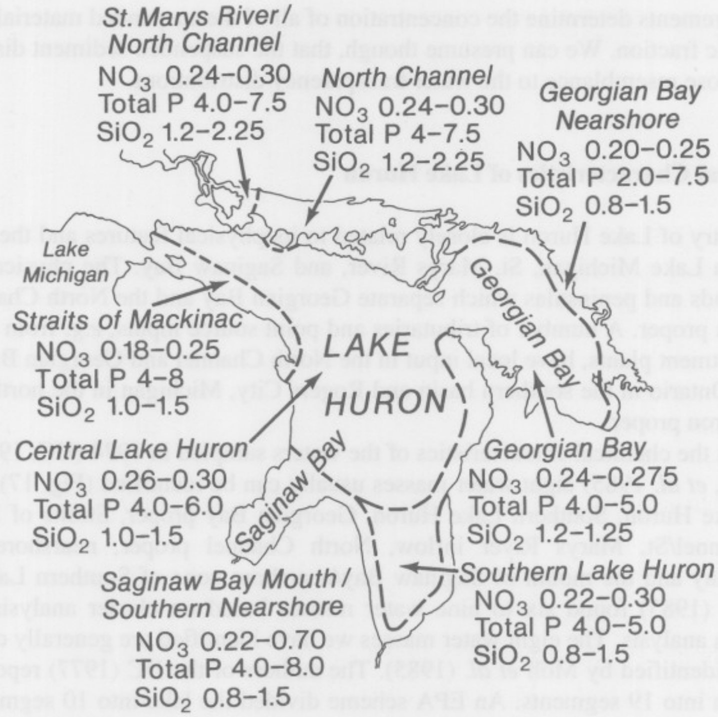

Fig. 17. Chemical characteristics of eight Lake Huron water masses (adapted from IJC, 1977).

epilimnion in summer. Once thermal stratification was established, all the nutrients had clinograde or heterograde distributions with lower concentrations in the epilimnion than in the hypolimnion. These seasonal changes in vertical distribution are due mostly to decreases in epilimnetic concentrations rather than increases in the hypolimnion.

Lake Michigan waters flowing through the Straits of Mackinac into northern Lake Huron had low nitrate concentrations of 0.18 to 0.25 mg N l^{-1} in 1980 (Moll *et al.*, 1985). Central Lake Huron values were 0.26 to 0.30 mg N l^{-1}. Concentrations of total phosphorus (4 to 8 μg P l^{-1}), ammonium (1 to 4 μg N l^{-1}), soluble reactive phosphorus (0.4 to 1.0 μg P l^{-1}), and silica (1.0 to 1.5 mg l^{-1}) were within the same ranges in the Straits and Central Lake Huron. Southern Lake Huron concentrations of these nutrients were also within the same ranges in values as above, although some ammonium concentrations of 6 μg N l^{-1} were observed and some silica values were 0.8 mg l^{-1}. The Saginaw Bay/nearshore southern Lake Huron waters had concentrations of nitrate up to 0.70 mg N l^{-1} and total phosphorus up to 8 μg P l^{-1}. The St. Marys River/North Channel had total phosphorus concentrations of 4 to 7.5 μg P l^{-1} and silica concentrations of 1.2 to 2.25 mg l^{-1} (Fig. 17). In general the waters of Georgian Bay and Central Lake Huron were closely similar. The highest concentrations of silica (2.25 mg l^{-1}) occurred in the North Channel, presumably due to river inflow. Ammonium concentrations were greatest in the southern Lake Huron nearshore (13 μg N l^{-1}), St. Marys River inflow (15 μg N l^{-1}) and nearshore of Georgian Bay (26 μg N l^{-1}) reflecting local anthropogenic inputs. Episodic discharges

Table 3. Average nutrient and major ion concentrations in Lake Huron.

	1900[a]	1956[b]	1974[c]	1980[d]
Calcium mg/l	26.5	26.7	25.1	26.4
Magnesium mg/l	6.3[e]	7.2	7.1	-
Sodium mg/l	4.0[f]	2.54	3.1	3.3
Potassium mg/l	-	0.85	0.8	1.0
Alkalinity mgCaCo3/l	-	75.9	78.6	-
Chloride mg/l	5	5.9	5.4	5.6
Silica mg/l	-	1.9	1.2	1.3
Sulfate mg/l	8	13	14.4	15.5
Conductance μmhos	-	174	201	201
Total P μP/l	-	-	5.3	4.6
Nitrate mgN/l	-	-	0.27	0.28

[a]Beeton 1969
[b]Southern Lake Huron (Allen, 1964)
[c]Calculated from Table 5.3-11 and 5.33-12 (IJC, 1977)
[d]Northern Basin Lake Huron (Moll et al., 1985)
[d]Northern Basin Lake Huron (Moll et al., 1985)
[e]Beeton 1971
[f]Sodium + potassium

of ammonium can be traced through the Bay at times (Sly & Munawar, 1988). Moll *et al.* (1985) concluded that the physical environment controlled the location of water masses, whereas the biota determined the concentrations of nutrients within the water masses. Added to this conclusion should be the recognition of the importance of continued nutrient loadings from local rivers, sewage outfalls, and major inputs from Lake Michigan, Saginaw Bay, and the St. Marys River or maintaining areal differences.

The major cations in all Lake Huron waters are calcium>magnesium>sodium> potassium (Table 3). The waters are bicarbonate as shown by alkalinity with sulfate and chloride being the next most abundant anions. Data presented in Table 3 are for the open waters of Lake Huron, which are primarily a mixture of waters from Lake Michigan, Lake Superior and Georgian Bay. For example, Lake Michigan waters in the Straits of Mackinac had a mean chloride concentration of 6.5 mg l^{-1} in 1974 (IJC, 1977, Fig. 5.3-9), whereas the St. Marys River water flowing into the North Channel had a mean chloride concentration of 2.6 mg l^{-1}. Open Georgian Bay waters had mean chloride concentrations of 4.8 mg l^{-1} (IJC, 1977, Fig. 5.3-11). Central Lake Huron, which is a mixture of these waters, had a mean chloride concentration of 5.4 mg l^{-1}. In flowing Saginaw Bay water, increased chloride levels at the mouth of the Bay to a mean of 6.0 mg l^{-1} of chloride and resulting southern basin mean concentrations of chloride of 5.8 mg l^{-1}.

The small differences in average concentrations of chemicals shown in Table 3 are

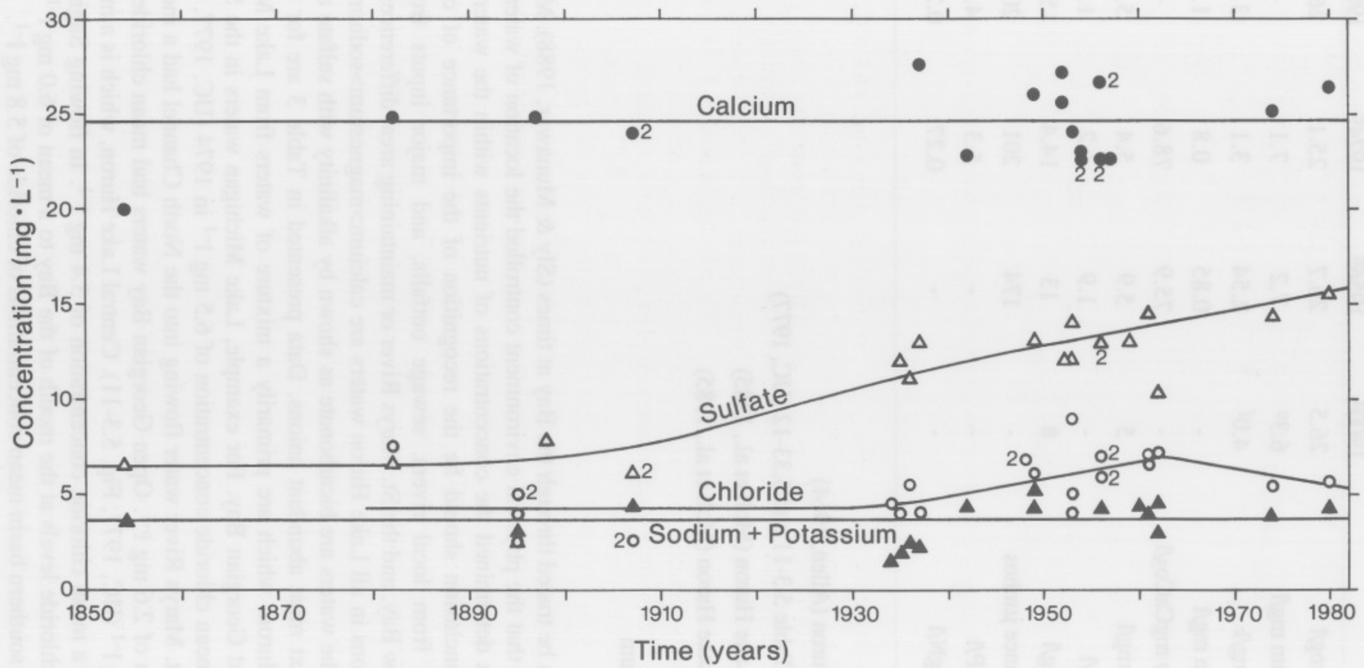

Fig. 18. Changes in chemistry of Lake Huron water (adapted from Beeton, 1969, recent data from Moll *et al.*, 1985).

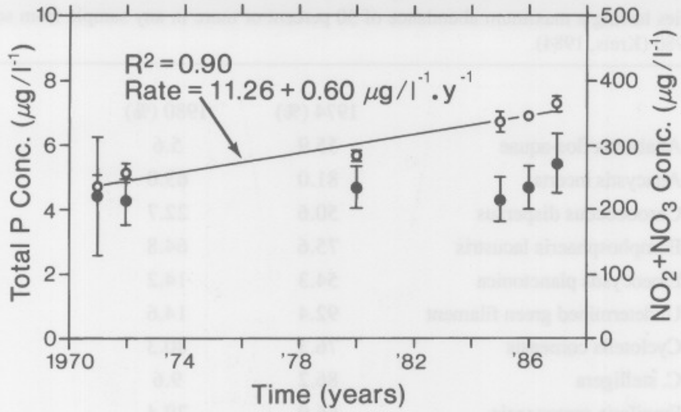

Fig. 19. Changes in nitrate (open circle) and total phosphorus (closed circle) concentrations in Lake Huron water (from IJC, 1989).

most likely a consequence of location, time, methods of sampling, and differences in laboratory analyses. Few data are available on nutrient concentrations prior to 1960, and the early data are not reliable. Earlier data for sodium and potassium usually combine these two elements, although the combined results are generally compatible with more recent data. The reason for the low specific conductance in 1956 relative to 1974 and 1980 is unknown, especially since the 1956 data are for southern Lake Huron and presumably should be greater than measurements for northern Lake Huron.

Beeton (1969), through use of historical data from many sources, demonstrated increases in chloride and sulfate for Lake Huron waters (Fig. 18). More recently, Moll *et al.*, (1985) used several approaches to identify and verify long-term trends in Lake Huron chemistry. They concluded that sulfate and nitrate increased and silica and chloride decreased. The sulfate increase is compatible with the trend observed by Beeton (1969), whereas chloride concentrations have decreased.

The IJC (1989) published data which indicate that nitrate continues to increase whereas total phosphorus concentrations show no changes since 1971 (Fig. 19). The increases in nitrate have caused concern (IJC, 1989). Nevertheless, the waters of Lake Huron continue to have the low nutrient concentrations of an oligotrophic lake (Dobson, *et al.*, 1974). As would be expected, the dissolved oxygen concentrations in all areas except in a few nearshore sites are near saturation.

11. Plankton

The phytoplankton communities of Lake Huron, Georgian Bay, and North Channel are those recognized as favored by oligotrophic conditions. However, because of the several water masses usually present in Lake Huron, a broad spectrum of algal populations are present ranging from those associated with oligotrophic to eutrophic conditions (IJC, 1977). Central Lake Huron, southern Lake Huron, and the offshore waters of Georgian Bay and North Channel have phytoplankton communities dominated by diatoms,

Table 4. Algal species having a maximum abundance of 50 percent or more in any sample from southern Lake Huron in 1974 or 1980 (Kreis, 1984).

	1974 (%)	1980 (%)
Anabaena flos-aquae	55.9	5.6
Anacystis incerta	81.0	63.0
Chroococcus dispersus	50.6	22.7
Eomphosphaeria lacustris	75.6	64.8
Eloeocystis planctonica	54.3	14.2
Undetermined green filament	92.4	14.6
Cyclotella comensis	76.3	80.3
C. stelligera	86.2	9.6
Fragilaria crotonensis	66.0	29.4
F. capucina	32.5	52.3
Undetermined flagellate sp. 15	-	69.7
Undetermined flagellate spp.	26.4	58.6

chrysomonad, and cryptomonad flagellates associated with oligotrophy (IJC, 1977; Munawar *et al.*, 1988). Saginaw Bay mouth/nearshore southern Lake Huron have assemblages of species favored by mesotrophic and/or eutrophic conditions. Species such as *Fragilaria capucina* and various blue-green alga are especially prevalent (Tables 4 and 5). The St. Marys River contributes to the species richness in northern Lake Huron, since as much as 25 percent of the algal volume in this area may be benthic diatoms carried in the river plume (Kreis *et al.*, 1983).

A bimodal distribution has been observed in the seasonal abundances of phytoplankton with a spring maximum, summer minimum, weak fall increase, and a somewhat lower winter population (IJC, 1977). Biomass estimates are 200 to 300 mg m^{-3} in the North Channel, and 400 mg m^{-3} in Georgian Bay and Central Lake Huron.

Concentrations of chlorophyll *a* reflect the oligotrophic conditions of the lake. Mean concentrations in Central Lake Huron and southern Lake Huron were 1.4 μg l^{-1} in 1974 (IJC, 1977). Mean chlorophyll concentrations were slightly greater in the Straits of Mackinac and North Channel (2.1 and 1.5 μg l^{-1}) reflecting the inflow of Lake Michigan and St. Marys River water. Chlorophyll *a* concentrations were 0.91 μg l^{-1} in open waters of Georgian Bay. Results of the 1980 surveys indicate the chlorophyll *a* concentrations and distributions (Moll *et al.* 1985) were similar to those of 1974. Glooschenko *et al.* (1973) also reported chlorophyll *a* concentrations of 1 to 2 μg l^{-1} for open Lake Huron. They also reported on the relationship of chlorophyll *a* to primary productivity and found that the productivity ranged from 2.0 to 3.0 mg ^{14}C m^3 h^{-1} from April to December, 1971.

The phytoplankton of Lakes Huron and Michigan are closely similar in their photosynthetic characteristics. The maximum photosynthetic rate at light saturation was 2.3 mg C mg Chl^{-1} h^{-1} in Lake Huron and 2.4 mg C mg Chl^{-1} h^{-1} in Lake Michigan (Fahnenstiel *et al.*, 1989). Furthermore, the percent of ^{14}C O_2 incorporated into proteins, lipids, polysaccharides, and low molecular weight metabolites were very similar for the phytoplankton of the two lakes.

Table 5. Algal species comprising four percent or more of the average phytoplankton population in southern Lake Huron, 1974 and 1980 (Kreis, 1984).

	1974 (%)	1980 (%)
Cyanophyta	13.5	18.9
Anacystis incerta	4.5	6.5
Gomphosphaeria lacustris	4.5	5.7
Chlorophyta	20.2	5.4
Bacillariophyta	55.7	35.5
Cycolotella comensis	8.6	16.9
C. stelligera	6.4	1.2
Fragilaria crotonensis	7.6	3.0
Synedra filiformis	4.4	1.0
Tabellaria fenestrata	4.3	1.8
Chrysophyta	4.7	11.1
Cryptophyta	1.3	8.8
Rhodomonas minuta var. nannoplanetiaca	0.8	4.9
Pyrrhophta	0.1	0.3
Euglenophyta	0.001	0
Undetermined flagellates	4.5	19.9

Recent research has shown that phototrophic picoplankton are abundant in Lakes Huron and Michigan (10,000 to 220,000 cells ml^{-1}) and contribute an average of 17 percent of the primary production and perhaps as much as 40 percent when the lakes are stratified (Fahnenstiel & Carrick, 1992). *Synechococcus* cyanobacteria are especially important picoplankton for the surface mixed-layer primary production in both lakes (Fahnenstiel *et al.*, 1991).

Makarewicz & Bertram (1991) concluded that the close similarities in predominant species and in phytoplankton biomass indicated no detectable change in the trophic status of Lake Huron proper from 1971 to 1985. Diatoms have been the major component of the phytoplankton. *Asterionella formosa, Cyclotella comensis, C. comta, C. ocellata, Fragilaria crotonensis. Melosira islandica, Tabellaria flocculosa,* and *Rhizosolenia* spp. were predominant diatoms in 1971, 1983, 1984, and 1985. *Cryptomonas erosa* and *Rhodomonas minuta* var. *nannoplanktica* were major Cryptophyta. The *Cyclotella* spp. (except for *C. comensis), Rhizosolenia eriensis. Dinobryon* spp. comprise an assemblage associated with oligotrophy. Some other species, *e.g. T. flocculosa,* suggest mesotrophy, but the open Lake Huron waters can be considered oligotrophic.

Changes indicating some nutrient enrichment have occurred in the phytoplankton community over 200 years. Microfossil diatom frustules in a core from southern Lake Huron suggests some shift from an ultra-oligotrophic *Cyclotella* spp. complex to species favored by nutrient enrichment, *e.g. C. comensis., M. granulata* and other taxa presumably associated with eutrophic Saginaw Bay waters. (Wolin *et al.*, 1988).

Lake Huron proper has a wide diversity of planktonic crustaceans. Patalas (1972) recorded 23 species in samples collected in August 1968. Ten of these species, five copepods and five cladocerans, made up more than 1 percent of the crustacean plankton

Table 6. Occurrence of crustacean plankton in Lake Huron (LH), Georgian Bay (GB), North Channel (NC), and Lake Superior (LS) (adapted from Patalas, 1972 and Carter & Watson, 1977). X indicates occurrence greater than 1 percent. P, present, but less than 1 percent.

	LH	GB	NC	LS
Limnocalanus macrurus	P	P	P	X
Diaptomus sicilis	X	P	P	X
D. ashlandi	X	X	X	X
D. minutus	X	X	P	X
D. oregonensis	X	P	P	P
Cyclops bucuspidatus	X	X	X	X
Daphnia retrocurva	X	P	P	X
D.longiremis	X	P	X	
D. galeata mendotae	P	X	P	X
Bosmina longirostris	X	X	X	X
Eubosmina coregoni	X	P	P	
Holopedium gibberum	X	P	P	P
Senecella calanoides		X	X	P
Eurytemora affinis	X		X	P
Tropocyclops prasinus	X		X	
Mesocyclops edax	X	X	X	P
Epischura Lacustris	X	X	X	P
Diaptomus siciloides	X			
Cyclops vernalis	X	X	X	P
Ceriodaphnia lacustris	X	X	X	P
Chydorus sphaericus	X	X	X	P
Diaphanosoma leuchtenbergianum	X	X	X	P
Leptodora kindtii	X	X	X	P
Polyphemus pediculus	X	X	X	P

(Table 6). The dominant species were *Cyclops bicuspidatus thomasi* followed by *Diaptomus sicilis, D. ashlandi,* and *D. minutus.* The cladocerans were less important. *Holopedium gibberum* and *Bosmina longirostris* were the most abundant.

The same species as found in Lake Huron proper occurred in Georgian Bay and the North Channel in 1974 (Table 6). The dominant copepods were *C. bicuspidatus* and *D. ashlandi* in the North Channel and these two species plus *D. minutus* were dominant in Georgian Bay (Carter and Watson, 1977). The major cladoceran was *B. longirostris.* The total number of species in the North Channel was 23. Georgian Bay had 22, since *Eurytemora affinis* was not found in the Bay.

Differences in crustacean communities may be related to nutrient loading to the Great Lakes (Patalas, 1972). Fewer diaptomids and greater abundances of cyclopoids and cladocerans seem to be related to increasing nutrients. Furthermore, some authors have used indicator species as evidence of the trophic state of a lake, *i.e.*, citing *B. longirostris* as the "ultimate eutrophic organism" and *D. sicilis* as an oligotrophic species (IJC, 1977).

The species assemblages for Lake Huron, Georgian Bay, and North Channel are closely similar to that of Lake Superior (Table 6). The same species dominate in the four ecosystems, including *B. longirostris* (Evans, 1983). It appears that the three calanoid copepods, *D. sicilis, D. ashlandi,* and *D. minutus* do well in oligotrophic systems, as does *B. longirostris.* The importance of this latter species in these nutrient poor, oligotrophic systems suggest it is inadvisable to call *B. longirostris* an eutrophic indicator.

Copepods make up the greatest percentage of the biomass in the North Channel and Georgian Bay, 76 to 79 percent of the mean seasonal biomasses of 229.5 and 224.8 mg. l^{-1} (Sprules *et al.*, 1988). Cladocerans comprised 16 to 19 percent of the mean seasonal biomass. Rotifers and other invertebrates were of minor importance.

Rotifers may be of minor importance in biomass estimates, but they are an important component in the food web of Lake Huron, especially for feeding on small algal cells (Ross *et al.*, 1983). Rotifers are abundant in Saginaw Bay, up to 1400 l^{-1}, but mean number per liter for eight cruises in Southern Lake Huron, April to November, 1974, was 63.2 to 401 (Stemberger *et al.*, 1979). Two species were predominant in Saginaw Bay as well as in open Lake Huron, *Notholca foliacea* and *Synchaeta lakowitziana. N. squamula* and *N. laurentiae* were the other major open lake species. These are probably not oligotrophic indicators, but cold stenotherms. Saginaw Bay species frequently dominated the southern Lake Huron nearshore.

Recent studies have demonstrated the importance of protozoans, since they are numerically important in the plankton with a ciliate average biomass of 50 μg l^{-1} (Carrick & Fahnenstiel, 1990). These authors estimated that heterotrophic ciliated and flagellated protozoa have a biomass of greater than 80 percent that of the crustacean biomass, and therefore, account for a significant amount of community metabolism and grazing of microbial production. The ciliate and dinoflagellate communities are closely similar between Lakes Huron and Michigan being dominated by choreotrichs and oligotrichs. Ciliate abundances range from 2 to 14 cells ml^{-1} with a biomass of 9.9 to 87.3 μg l^{-1}. The protozoan community has two peaks, spring and fall with low numbers in winter. The protozoans probably provide an important link in the food web for transfer of microbial production to crustaceans which graze on the protozoa.

12. Benthic Communities

The benthos of Lake Huron proper is dominated by *Diporeia* sp. (*Pontoporeia affinis*), oligochaetes, sphaeriid clams, and chironomids (Barton, 1986; Schuytema & Powers, 1966; Shrivastva, 1974; Teter, 1960). The average abundance of macrobenthos ranged from 625 organisms m^{-2} in 1952 and 1958, to 1937 organisms m^{-2} in 1963 and 1964 (Teter, 1960; Barton, 1986) at depths less than 25 m. In waters deeper than 25 m, the organisms m^{-2} ranged from 627 (Schuytema & Powers, 1966) to 1640 (Teter, 1960).

Diporeia clearly dominates the benthos comprising 38 to 77 percent of the macrobenthos in all the studies. Shrivastava (1974) suggested a decline in the abundance of *Diporeia,* but Barton (1989) concluded it is unlikely that the abundance had changed significantly between 1955 and 1971. Differences may be in sampling methods, areas, and depths sampled.

Stylodrilus heringianus is the dominant oligochaete in Lake Huron proper, although other species are important in shallow areas affected by organic inputs. Oligochaetes comprised 9 to 37 percent of the benthos in the several studies (Barton, 1986). Only Teter (1960) found less than 22 percent of the benthos was oligochaetes.

Sphaeriidae make up 5 to 22 percent of the benthos (Barton, 1986). The lowest percentages were for samples taken in 1963 and 1964 (Barton, 1986). Only *Pisidium* spp. were reported for this family in the several studies. It is likely that *P. conventus* is the major species as it was about the only sphaeriid collected in Georgian Bay and Straits of Mackinac (Brinkhurst *et al.*, 1968).

A number of taxa of midges have been reported in the several surveys, but it is clear that the dominant chironomid is *Heterotrissocladius* sp., probably *H. olivri* (Barton, 1986).

The same organisms that are dominant in Lake Huron proper are dominant in Georgian Bay and the North Channel, although Loveridge & Cook (1976) reported nematodes as being second in importance to *Diporeia*. This also may be the situation in open Lake Huron, but it is not possible to compare the studies in this regard since Loveridge & Cook (1976) used a 0.1 mm screen and the other studies used 0.5 mm screens for processing the samples. Consequently, fewer nematodes would have been retained in most studies. The average abundance of benthic organisms was 3303 m^{-2} in Georgian Bay and 4636 m^{-2} in the North Channel in 1973 (Loveridge & Cook, 1976). A mean total of 4700 organisms m^{-2} in the North Channel in 1965 was reported by Schuytema & Powers (1966). They suggested that the greater abundance and biomass of benthic organisms in the North Channel was a consequence of organic material coming in from the St. Marys River.

The nearshore zone of western Lake Huron has benthic communities with a different species mix than found in the deeper offshore waters, *i.e.*, 30 m (IJC, 1977). At depths less than 20 m the communities are dominated by oligochaetes and chironomids. It is likely that the nearshore benthos elsewhere in Lake Huron proper, Georgian Bay, and the North Channel is closely similar to that occurring along the western shore of northern Lake Huron.

The importance of the outflow from Saginaw Bay to the limnology of Lake Huron is seen in the benthic communities at the mouth of the Bay and in the nearshore of the southern basin (Fig. 20). Pollution tolerant oligochaetes, *i.e.*, *Tubifex tubifex* and *Limnodrilus* spp., and eutrophic-mesotrophic types, *i.e.*, *Peloscolex ferox* and *Potamothrix* spp. (Brinkhurst, 1980) dominate the benthos in these areas, evidently as a consequence of organic materials coming from the Bay. These oligochaetes are abundant in southwestern Lake Huron, but not in nearshore Lake Huron north of Saginaw Bay.

Two midge genera, *Chironomus* spp. and *Tanytarsus* spp. are part of this nearshore benthic community. *Chironomus* spp. distribution is closely similar to that of the pollution tolerant oligochaetes, few occurred north of the Bay (Fig. 20). The distribution of *Tanytarsus* spp. in the nearshore of both northern and southern Lake Huron suggests that its occurrence is not greatly influenced by nutrients from Saginaw Bay, except for some larger populations at the Bay mouth and further south in the southern nearshore. (Fig. 20).

The zebra mussel, *Dreissena polymorpha,* has become an important addition to the nearshore benthos. Our research indicates it was in Lake Huron by 1990. A related species, the quagga mussel, *Dreissena bugensise*, occurs at greater depths than the zebra mussel in the lower lakes and it undoubtedly will become established in Lake Huron.

Mysis relicta is an abundant organism in the cold, deep waters of Lake Huron. It is sometimes included as part of the zooplankton or benthos. It is a free swimming organism which spends some time on the bottom but it also makes extensive diel vertical migrations into the metalimnion and sometimes the epilimnion (Beeton, 1960). It can feed on detritus, phytoplankton and zooplankton (Grossnickle, 1978), but it is also a predator on *Diporeia* (Parker, 1980). Consequently it is important in pelagic-benthic coupling. Mysids are especially important in the deep waters of the Great Lakes. Mysid densities increase with depths to 200 m in Lake Huron (Carpenter *et al.*, 1974). The mean annual density of mysids in Lake Huron is about 200 m^{-2} and the secondary productivity is estimated to be 1.5 g m^{-2} yr^{-1}, slightly less than estimates for Lake Michigan mysids (Sell, 1982).

The dynamics of the profundal benthic community is likely tied to the seasonal pulses of phytoplankton, especially diatoms (Johnson & Wiederholm, 1992). Their studies of pelagic-benthic coupling in Lake Vanern indicated that fluctuations in zoobenthos populations are correlated with interannual variability in diatom biovolume. The European relative of *Diporeia, Monoporeia affinis,* apparently feeds heavily on the spring and fall pulses of diatoms and stores lipids as an energy source for periods of low food supply. This pelagic-benthic coupling involving *Diporeia* is apparently important in Lake Michigan (Gardner *et al.*, 1990) and it is likely to be equally important in Lakes Huron and Superior.

13. Trophic Status and the Future

The biological, physical, and chemical characteristics of Lake Huron are those associated with oligotrophy (Beeton, 1969). Munawar and Munawar (1982) classified the Great Lakes on the basis of mean biomass and concluded that Lake Huron was oligotrophic, and the North Channel and Georgian bay were ultraoligotrophic. Little change has been observed other than small changes in concentrations in sulfate, silica, and chloride (Moll *et al.*, 1985) and some increase in diatoms favored by nutrient enrichment (Wolin *et al.*, 1988). As noted in the chemistry section, nitrate continues to increase, but phosphorus concentrations have not changed in the lake proper (IJC, 1989). The increase in nitrate is likely due to atmospheric input. The nature of the Lake Huron ecosystem is largely determined by major inflow of Lake Michigan and Lake Superior waters, human activities altering the terrestrial system and seriously impacting some rivers and harbors called "areas of concern," inflow of Saginaw Bay waters, and atmospheric deposition. Physicochemical and biological processes including particle dynamics, benthic-pelagic coupling, and sediment water exchange alter and modify the aforementioned major inputs to the system.

The major sources of water to the system are the inflows from Lakes Michigan and Superior. The combined inflow ranges from about 4400 to 5400 m^{-3} sec^{-1}, whereas the outflow at the St. Clair River ranges from about 4800 to 5800 m^{-3} sec^{-1}. Consequently, around 90 percent of the water supply comes from Lakes Michigan (50 percent) and Superior (40 percent). The quality of these waters is especially important to the quality of Lake Huron and Beeton (1965) suggested that increases in total dissolved solids, chloride, and sulfate concentrations were largely due to increases observed in Lake Michigan waters, since these chemicals did not increase in Lake Superior. Subsequently, he concluded that much of the increased chemical content can be attributed to urbanization

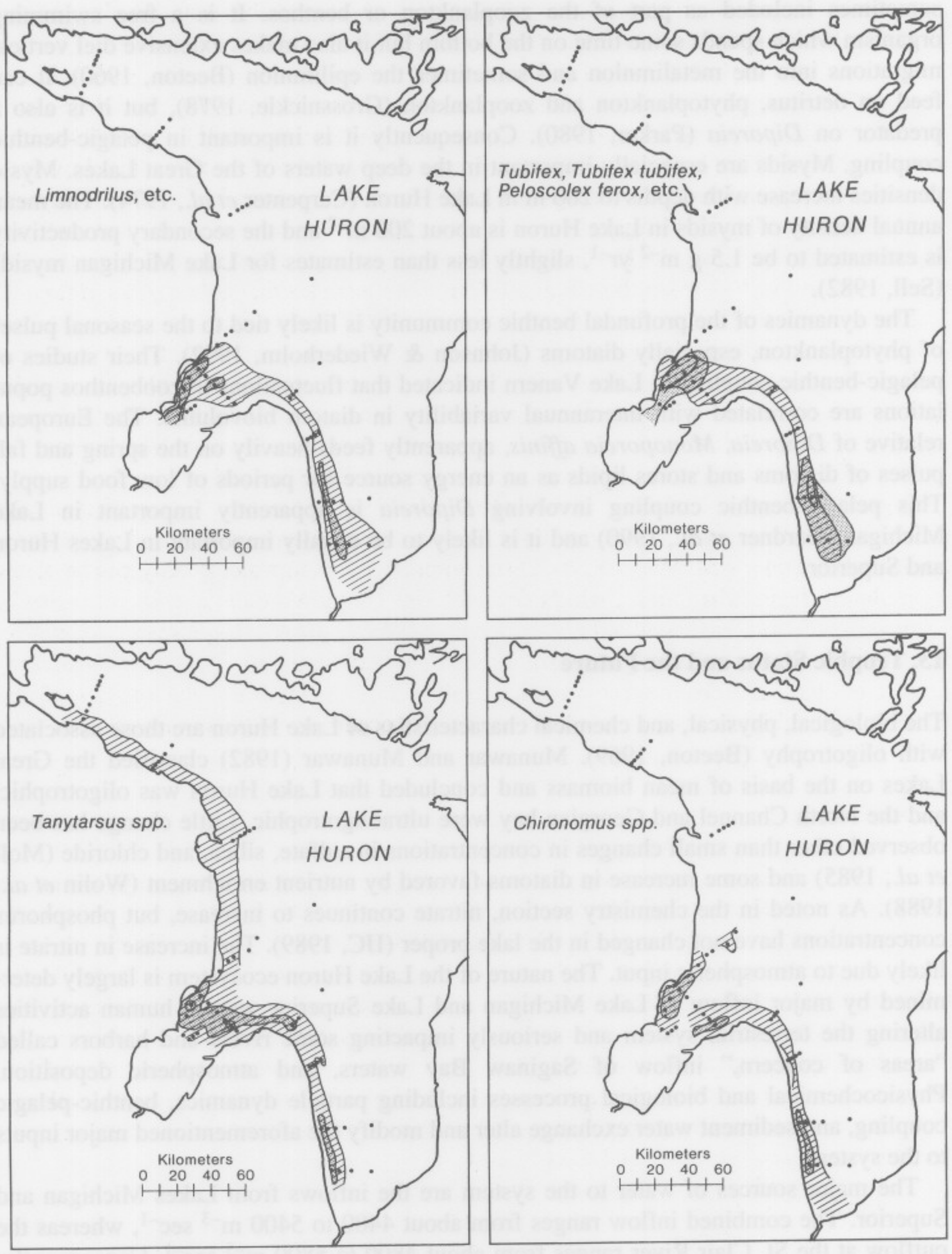

Fig. 20. Nearshore benthos of Lake Huron in 1972 (adapted from IJC, 1977). Dots are sampling sites. *Limnodrilus*, more darkly shaded areas are densities > 1,000 m^{-2} Tubificaidae designated by oblique lines, *Peloscolex* by stripes. *Tanytarsus* and Chironomidae, more darkly shaded areas are densities > 100 m^{-2}.

and industrial growth in the Saginaw Valley, which affects the water quality of the Saginaw River and the Bay (Beeton, 1969).

The "areas of concern" which affect ecosystem quality are the St. Marys River, Spanish River mouth in the North Channel, Saginaw River/ Saginaw Bay, and the Severn Sound and Collingwood Harbour of Georgian Bay (Hartig *et al.*, 1993). Nutrient loading to the St. Marys River has increased the nutrient content of these waters as they flow into the North Channel. Inputs of poor quality water from the Spanish River, Severn Sound, and Collingwood Harbour appear to have local impact. The outflow of the nutrient rich Saginaw Bay waters in Lake Huron proper have a significant importance to the nature of the lake, as shown by the benthos (Fig. 20). This demonstrates that although the inflow of Saginaw Bay water is less than 10 percent of the total basin supply, the pollution and nutrient enrichment of these waters can and has affected the trophic nature of the Lake Huron. Consequently, any remediation of Saginaw Bay will effect Lake Huron. An unknown factor is the large population of zebra mussels which have been established in the Bay since 1990. It appears that total phosphorus concentrations have been reduced as a consequence of the efficient filtering by the mussels (GLERL, 1994).

Implementation of "remedial action plans" (RAP's) in the five "areas of concern" should benefit the overall quality of Lake Huron, especially remediation of pollution in Saginaw Bay and the St. Marys River. These improvements in water quality can be offset by pollution from urban areas, which do not have RAP's. Furthermore, the increase in human population has been relatively small (Beeton, 1969). Significant population growth and concomitant changes in land use and increased pollution will have an adverse impact on the Lake Huron ecosystem. Sensitivity to maintaining the quality of the ecosystem should help lessen the impact of changes occurring in the drainage basin.

14. Summary

The physics, chemistry, and biology of Lake Huron are largely determined by five major features, viz. the Straits of Mackinac, which permits exchange of water with Lake Michigan; the inflow of the St. Marys River, which connects Lake Huron to Lake Superior; the Bruce Peninsula and several large islands, which separate the North Channel and Georgian Bay from the major basin; inflow of nutrient rich Saginaw Bay waters; and the major basin. These geological features plus land use activities in the watershed appear to be the major factors determining environmental quality and the biota. Information on the origin and nature of the Lake Huron basin, hydrology, chemistry, thermal regime, storm surges and seiches, currents, optical properties, plankton, and benthos have been presented and discussed.

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